New CEvNS limit from the CONUS experiment

On behalf of the CONUS Collaboration

Max-Planck-Institut für Kernphysik Heidelberg

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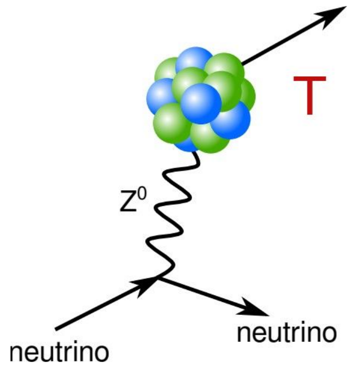
(MPIK)

Taup (Vienna), 29 August 2023

Coherent elastic neutrino nucleus scattering



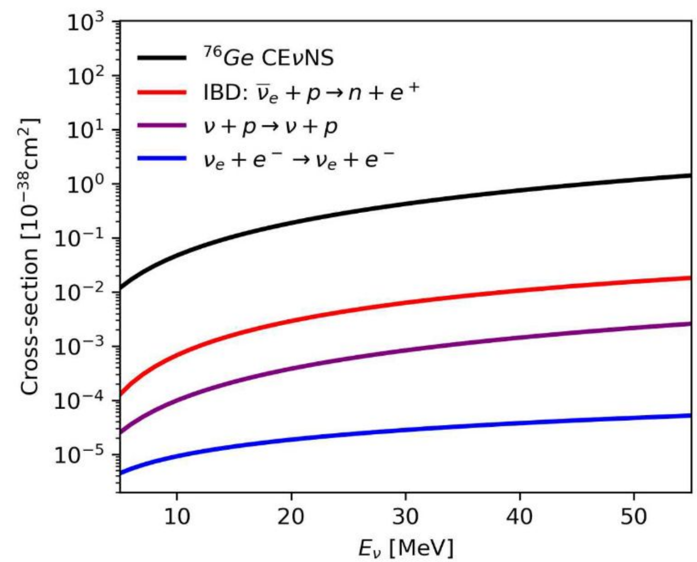
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi}\underbrace{\left[\mathrm{N} - \left(1 - 4\sin^2\theta_W\right)\mathrm{Z}\right]^2}_{\theta_W \sim\ 0.238\ \rightarrow\ N^2} M\left(1 - \frac{MT}{2E_\nu^2}\right)\underbrace{F^2(q^2)}_{1}$$

Low momentum transfer → full coherence (in Ge E_ν< 20 MeV).

CEvNS cross section is "large". Small, potentially mobile neutrino detectors feasible.

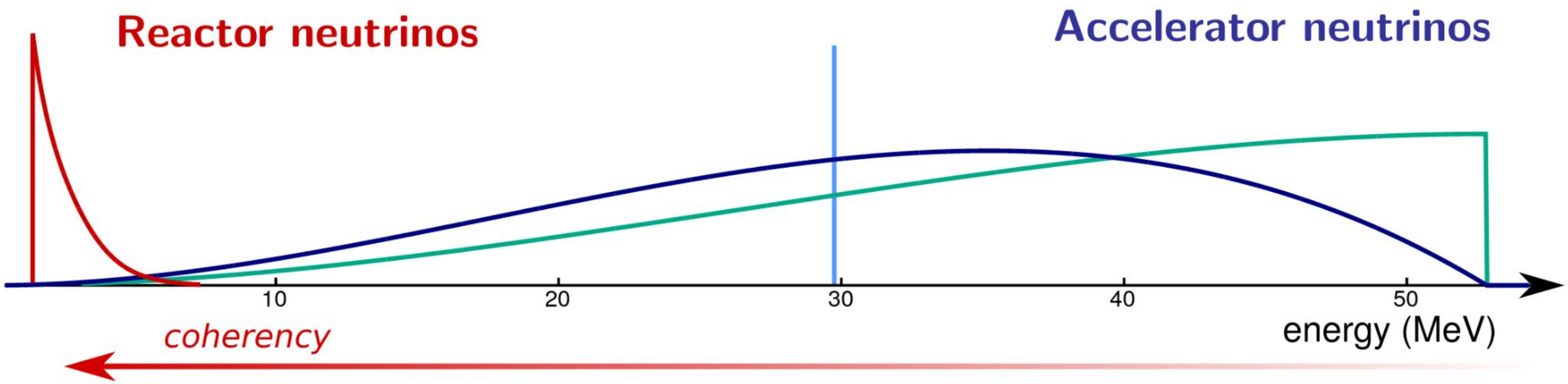
Experimental signature: low energy recoil of the nucleus:

$$T_{Max} \approx \frac{2\,E_\nu^2}{m_n A}$$



<u>The isotope selection is a push-pull situation.</u>

Experimental detection of CEvNS



$\bar{\nu}_e$ from β-decays of fissile isotopes.

Pure flux of $\bar{\nu}_e$.

E_ν ~ 0-10 MeV (fully coherent → F ~ 1).

Still no observation. Many experiments ongoing.

ν from π-DAR.

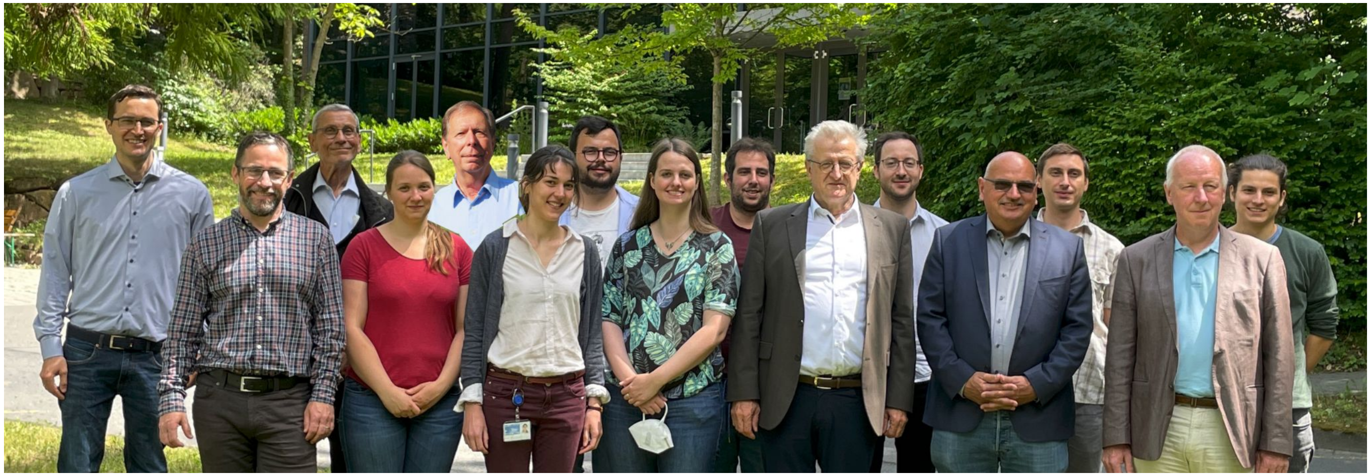
Different neutrino flavors.

E_ν ~ 20-50 MeV (F < 1).

Observation by COHERENT with CsI[Na] in 2017 and with Ar in 2020.

<u>Complementary experiments</u>

CONUS Collaboration



Max Planck Institut fur Kernphysik (MPIK)

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

N. Ackermann, S. Armbruster, H. Bonet, A. Bonhomme, C. Buck, J. Hakenmüller, J. Hempfling, G. Heusser, M. Lindner, W. Maneschg, K. Ni, T. Rink, E. Sanchez-Garcia, J. Stauber, H. Strecker

Former collaborators:
T. Schierhuber, E. Van der Meeren, J. Henrichs, T. Hugle

Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR)

K. Fülber and R. Wink

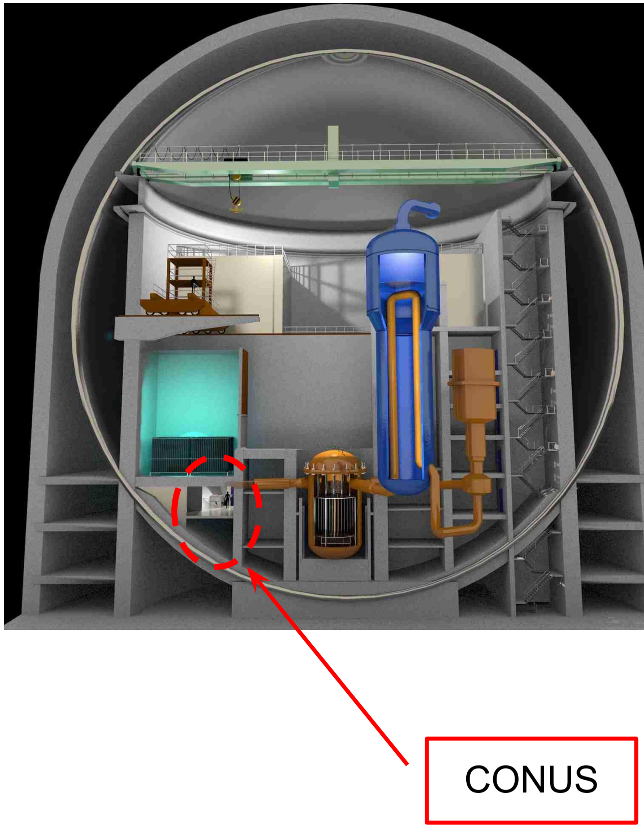
Preussen Elektra

Experimental site

CONUS was in the Brokdorf nuclear power plant (KBR) in Germany from 2018 to 2022.

<u>Experimental conditions:</u>

- 17 m from 3.9 GWth reactor core → high antineutrino flux expected 2.3 x 10^{13} $\bar{\nu}_e\, s^{-1} cm^{-2}$.
- High duty-cycle: 1 month/year of reactor-off.
- Shallow-depth site (24 m w.e.).



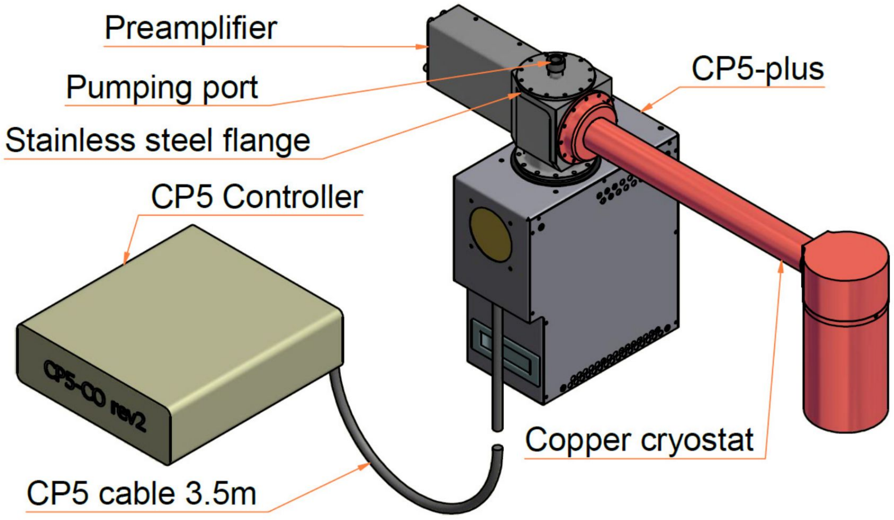
<u>Working conditions:</u>

- Strict access permission.
- Strict safety requirements.
- No cryogenic liquids

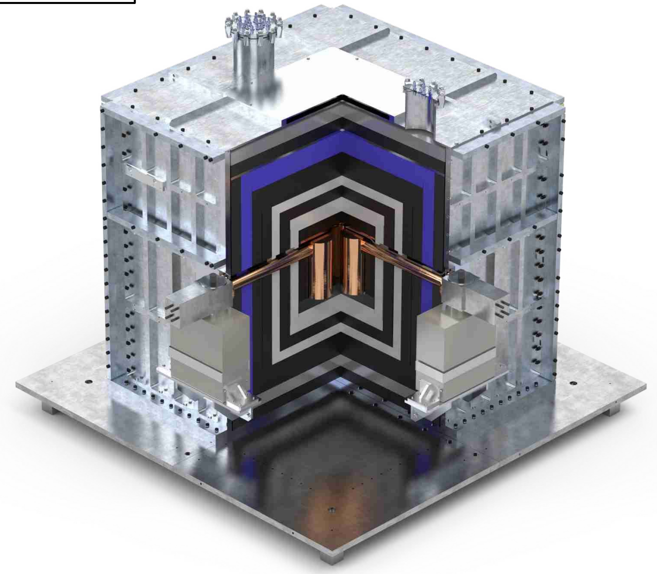
CONUS detector

4 p-type point contact HPGe:

- Total crystal/active mass: 4 kg /3.74kg.
- Pulser resolution (FWHM) < 80eVee.
- Energy threshold: 210 eVee.
- Radiopure components.



1.6 m^3
11 tons

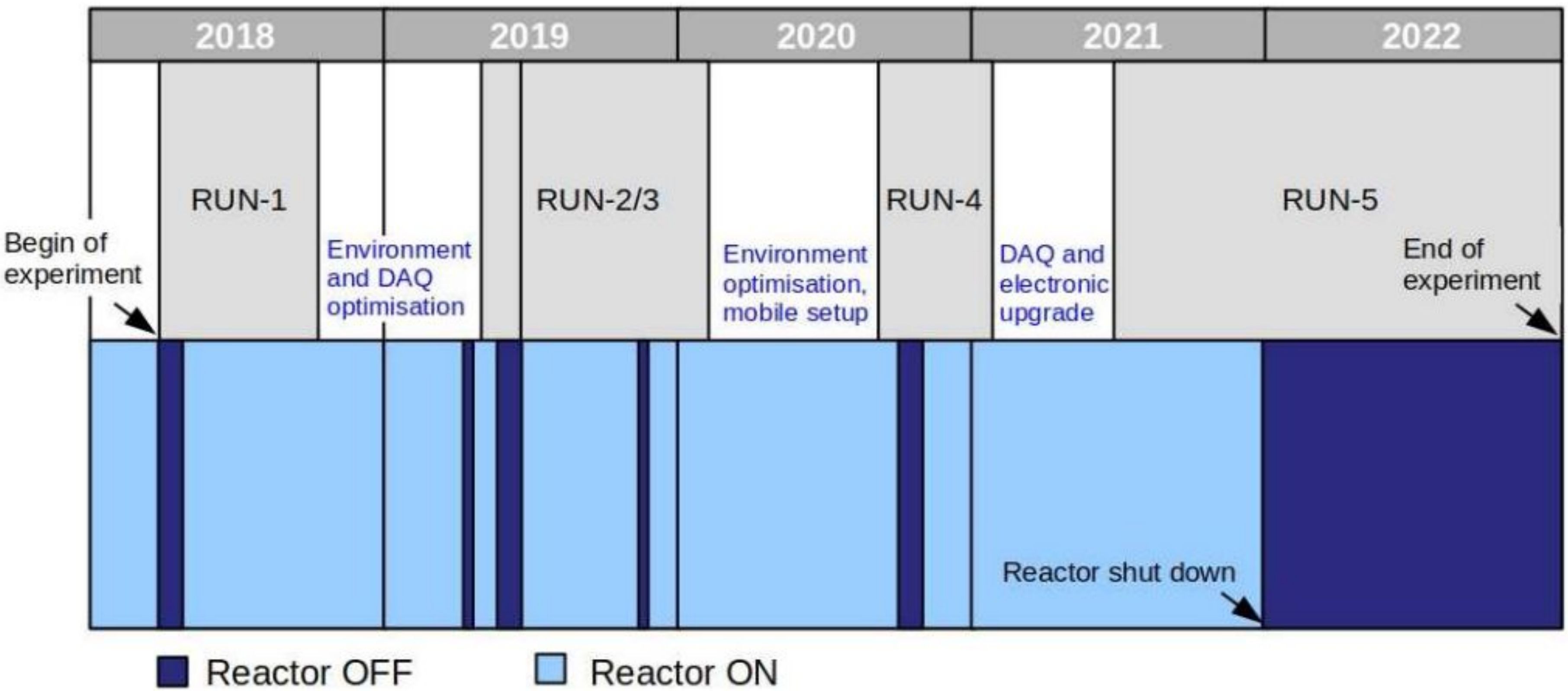


Active + passive shielding:

- Low ^{210}Pb lead.
- Borated and pure PE.
- Active μ-veto (plastic scintillator).
- Flushing again airborne radon.

CONUS Collaboration, Eur. Phys. J. C (2021) 81, 267

Data collection and reactor operation



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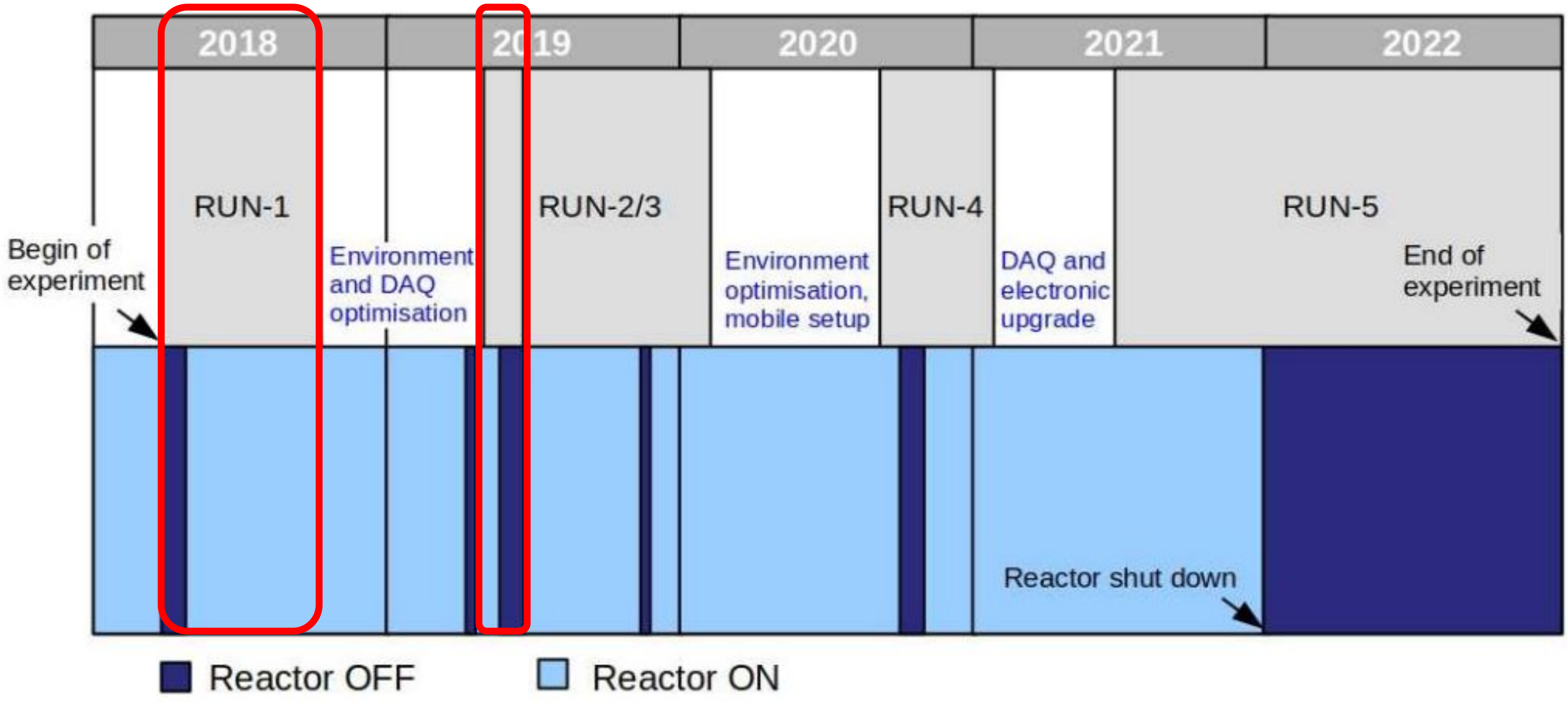

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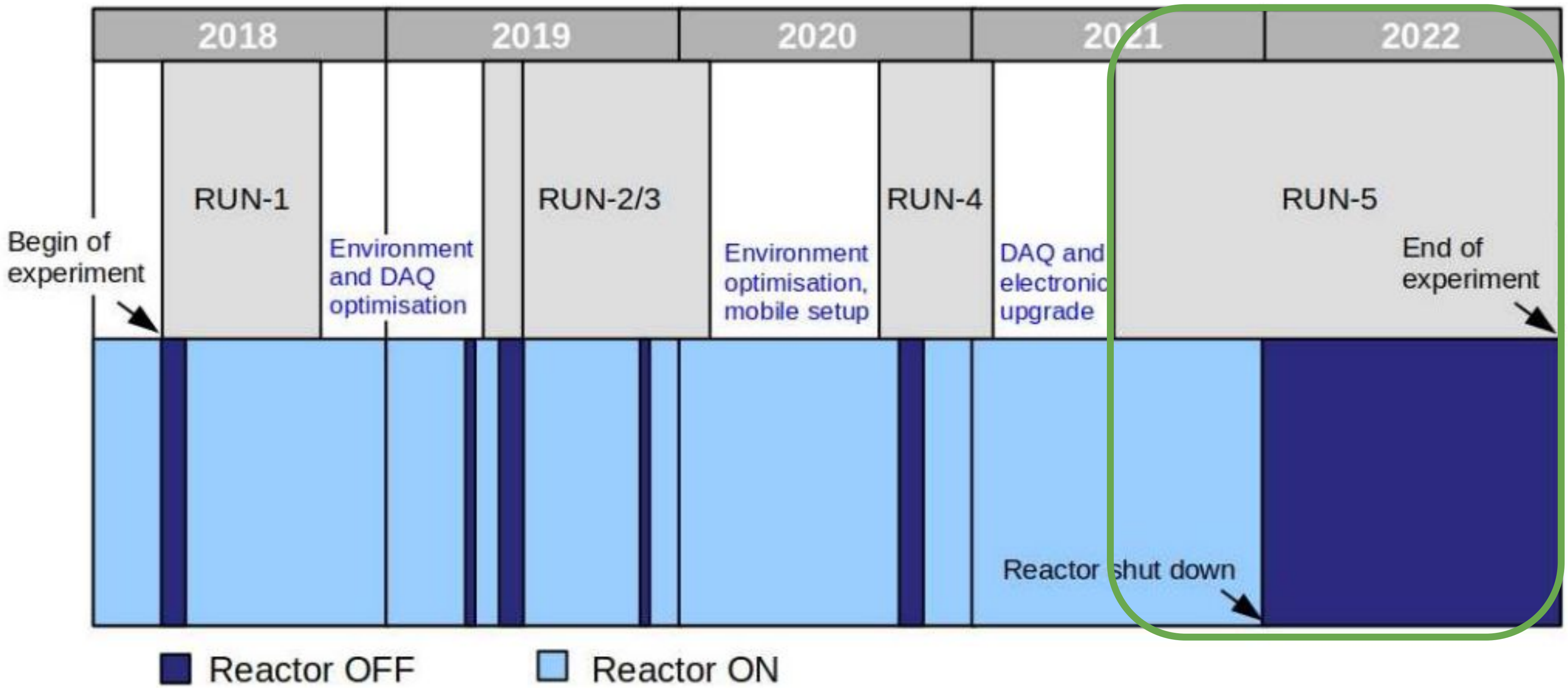


Run 1-2: CEvNS limit

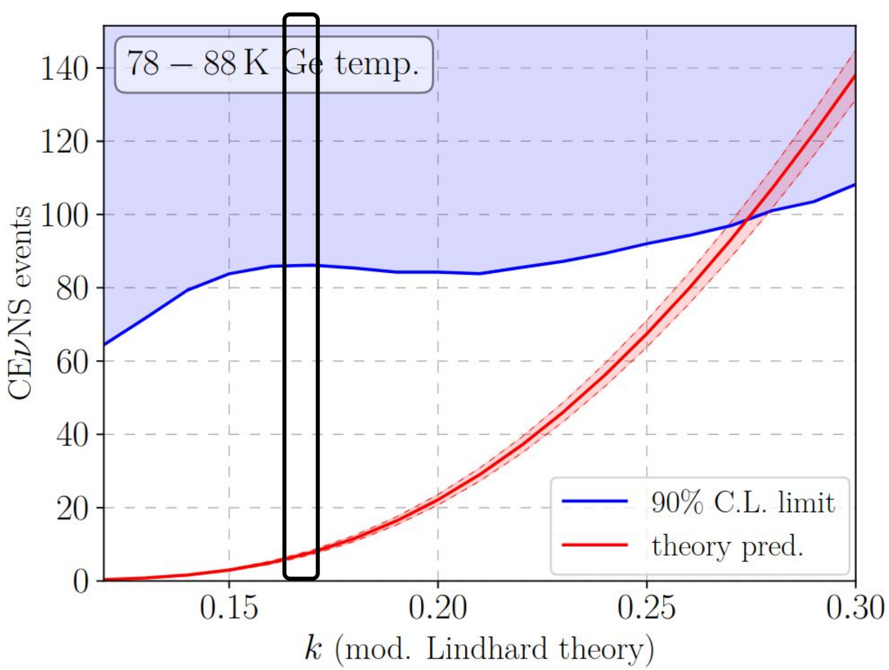
CONUS Collaboration, PRL 126 (2021) 041804

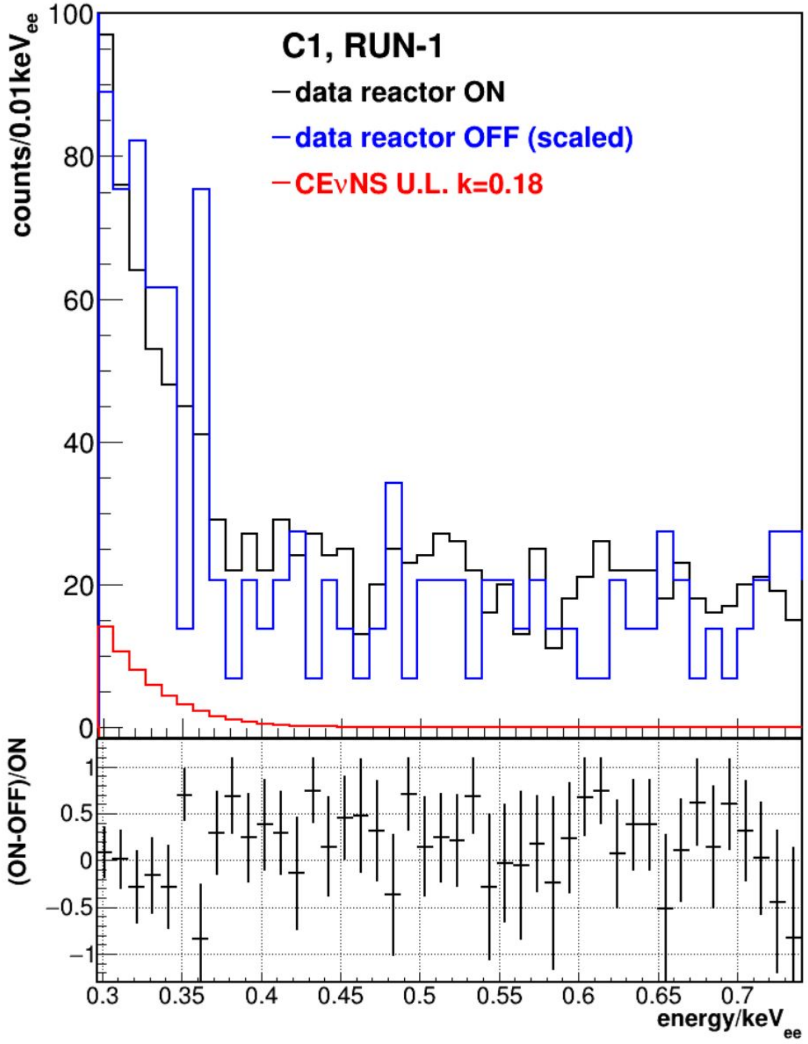
Exposure after cuts: 249 kg d reactor ON and 59 kg d reactor OFF. Region of interest: 0.3-1 keVee.

CEvNS limit at reactor: < 0.4 d^{-1} kg^{-1} (90 % C.L.) at k=0.16. Factor 17 over prediction.

Signal expectation depends on quenching factor described by Lindhard theory. k > 0.27 disfavored from CONUS reactor data alone.

Major systematics: quenching parameter



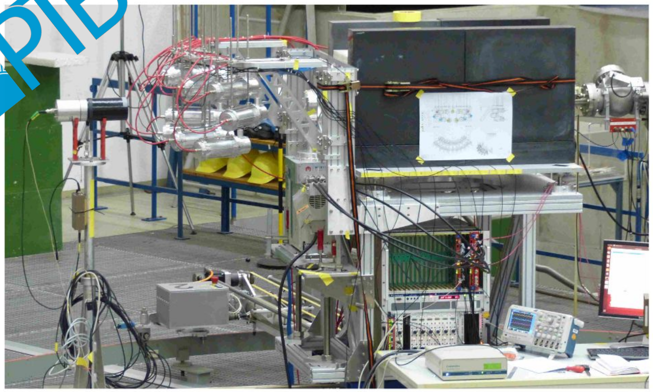


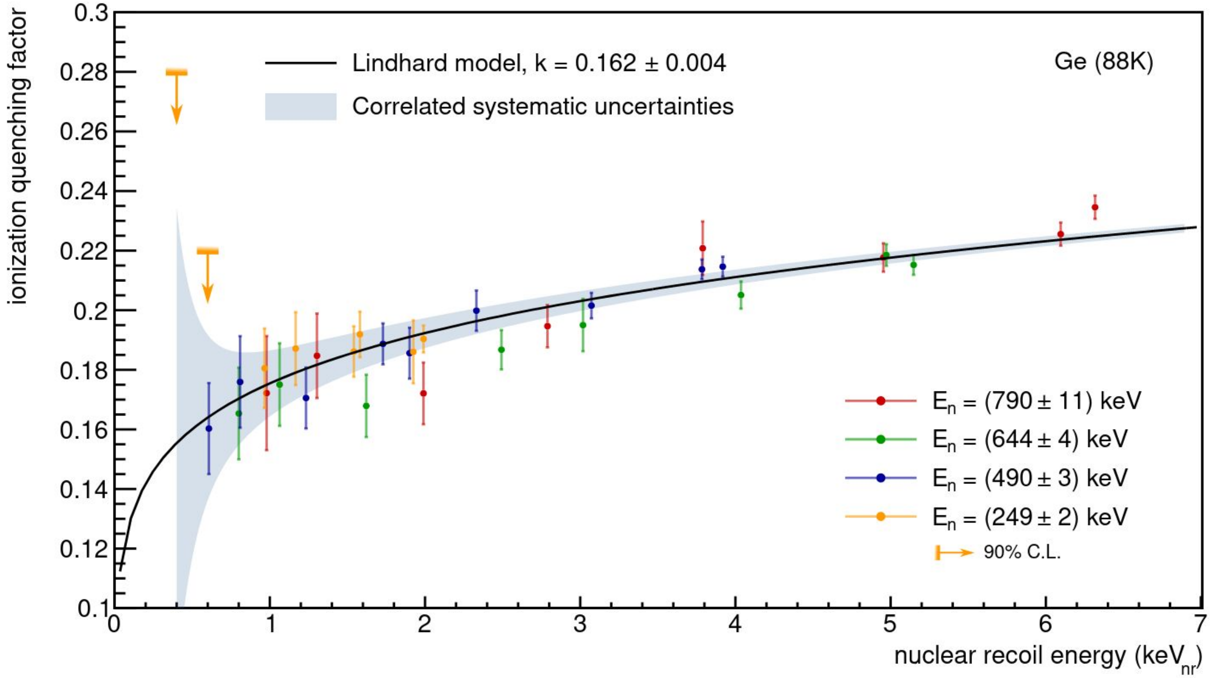
Quenching measurement

A. Bonhomme et al. , Eur. Phys. J. C 82, 815 (2022)

CONUS and PTB collaboration for a direct, model-independent (purely kinematics) measurement using neutrons (nuclear recoils).

All relevant systematic uncertainties included: setup geometry, beam energy, detector response including energy scale non-linearities.

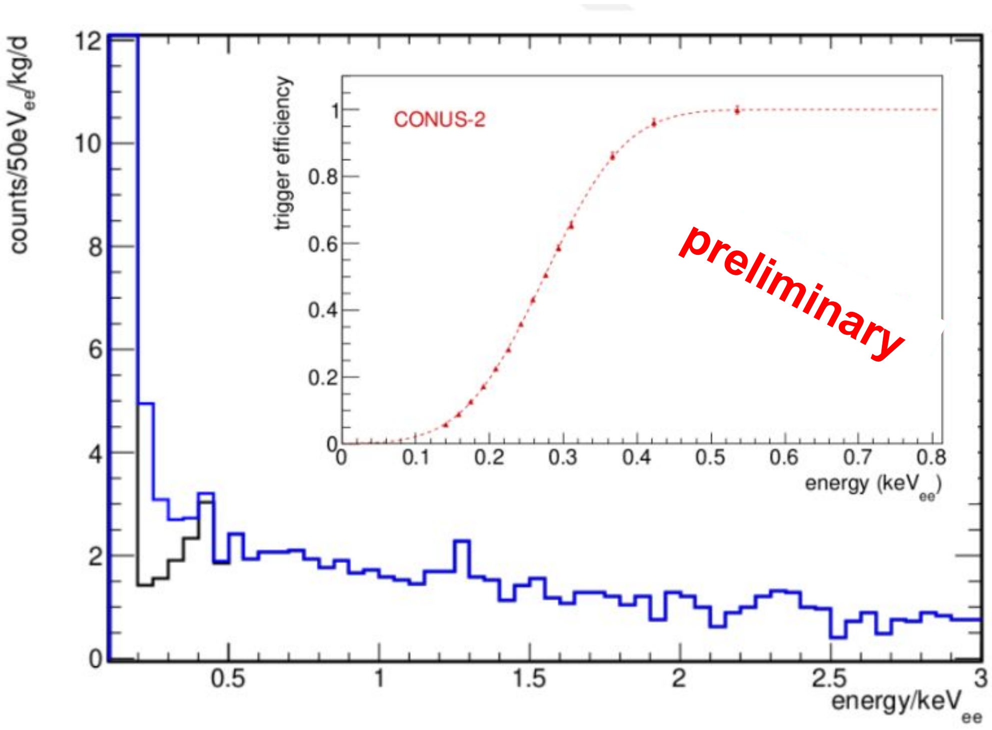




Data compatible with Lindhard theory down to sub-keV: <u>k = 0.162 ± 0.004 (stat+syst).</u>

Run-5 upgrade

- New DAQ → optimize trigger efficiency vs noise reduction → **new threshold 210 eV_{ee}**



Run-5 upgrade

CONUS Collaboration,
arXiv:2308.12105

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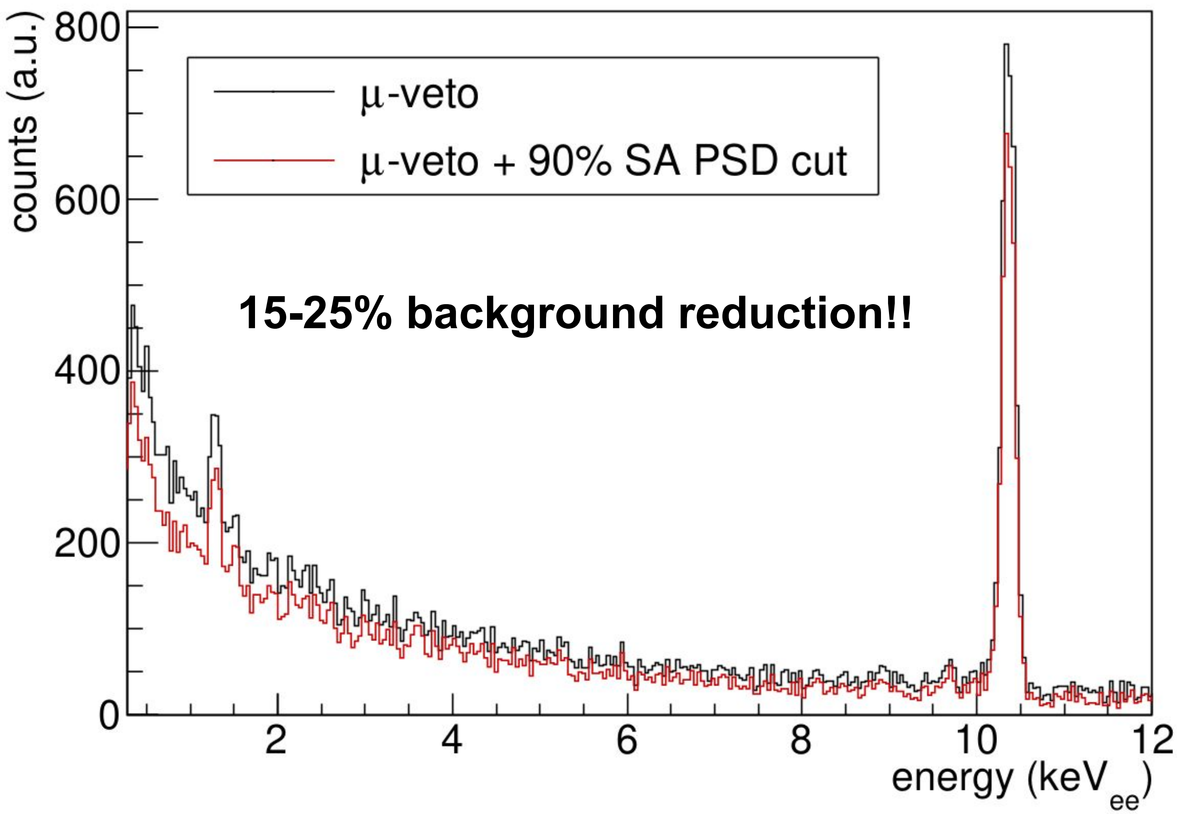
  → pulse shape background discrimination (see poster "Pulse-Shape Discrimination for the CONUS Experiment" by Janine Hempfling)



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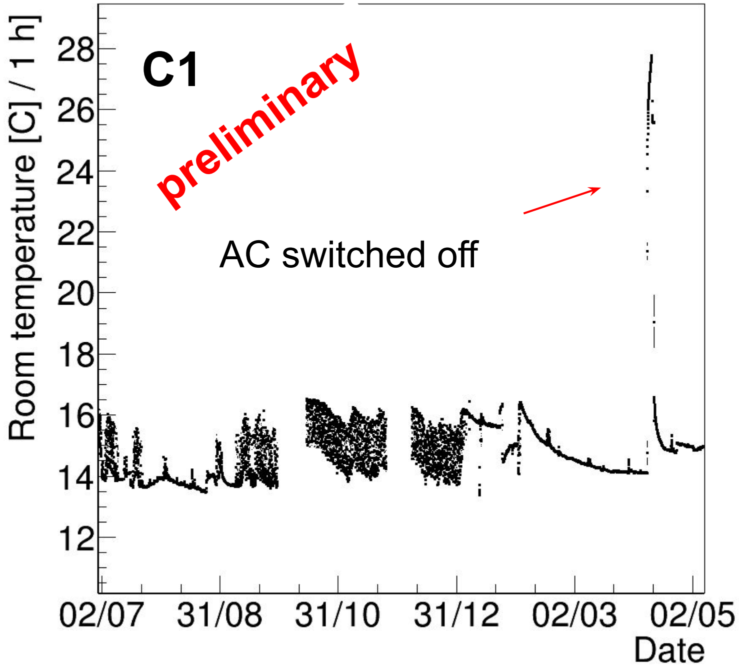
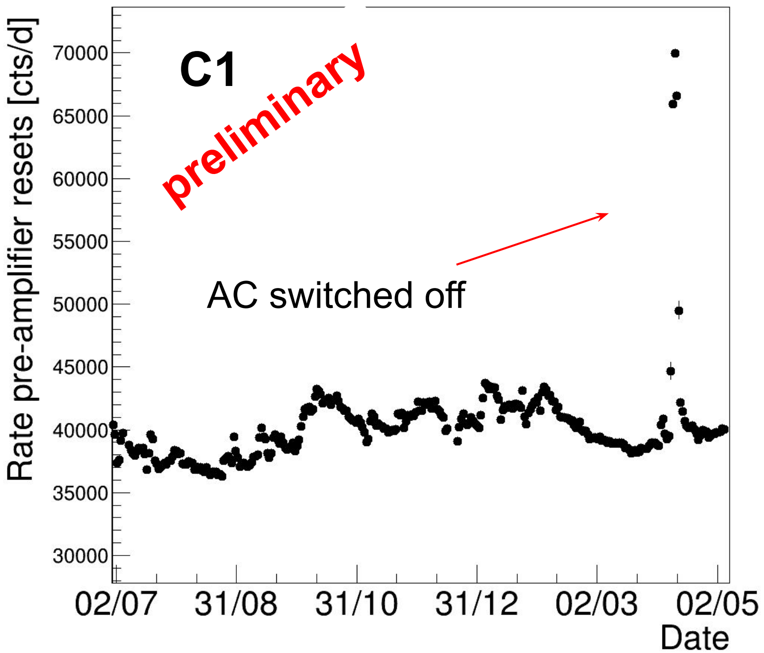
- 1 month ^{252}Cf neutron source irradiation → energy scale uncertainty 5 eV
- Improve stable/lower air temperature → reduce microphonics from cryocooler.
  Temperature stability < 1.5 °C





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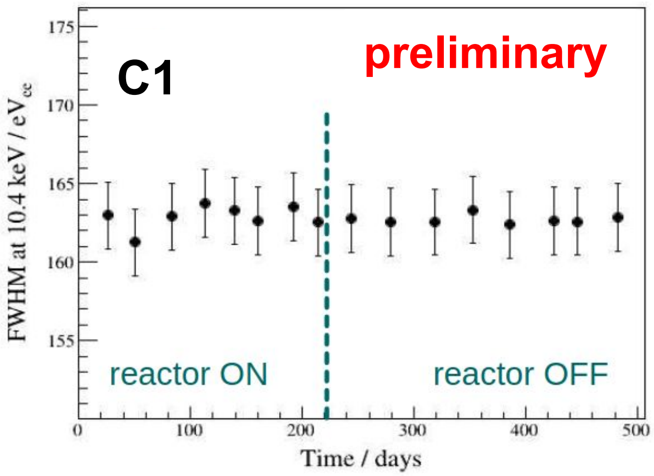
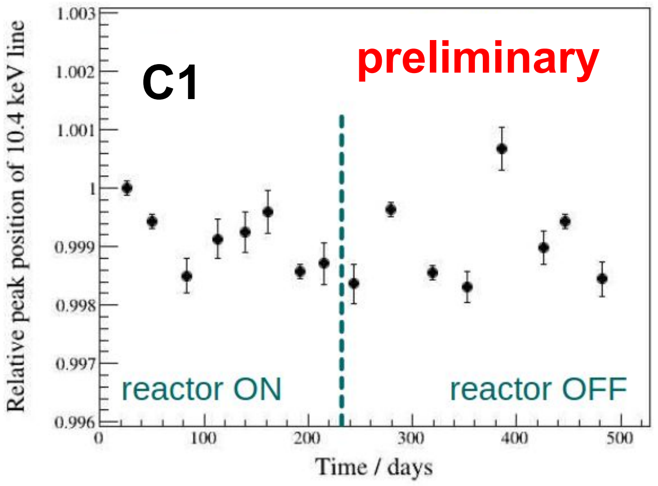
- 1 month ^{252}Cf neutron source irradiation → energy scale uncertainty 5 eV
- Improve stable/lower air temperature → reduce microphonics from cryocooler. Temperature stability < 1.5 °C
  → improve stability

FWHM of 10.4 keV line



Peak pos. of 10.4 keV line



Run-5 result

preliminary

Detector	Exposure ON/OFF [kg*d]	Threshold [eV]	Signal prediction (k=0.16)	Likelihood fit
C1	151 / 43	210	42 ± 8	<59
C2	154 / 138	210	26 ± 5	<75
C4	153 / 112	210	24 ± 4	<90
All	458 / 293		92 ± 10	<163

Preliminary combined two sided limit (90% C.L.): factor < 2 above predicted SM signal (Lindhard quenching with k=0.162). Publication in preparation.

~ one order of magnitude improvement as compared to Run-1+2!

<u>Strongest limit on reactor CEνNS!!</u>

Comparison with other experiments

Current results from reactor CEvNS experiments:

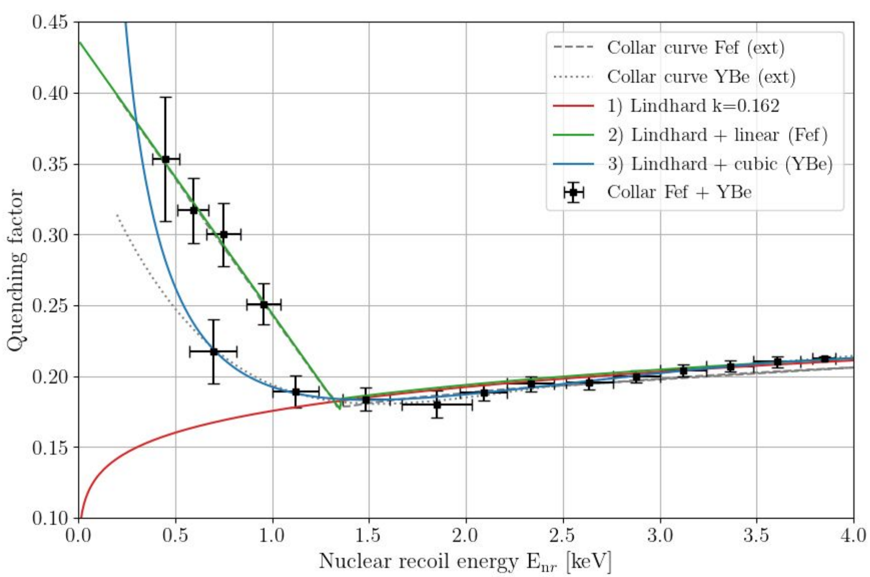
- Constraints from vGen, CONNIE, Texono, …
- Strong signal preference with NCC-1701 using alternative quenching description (Phys. Rev. D 103, 122003 (2021))

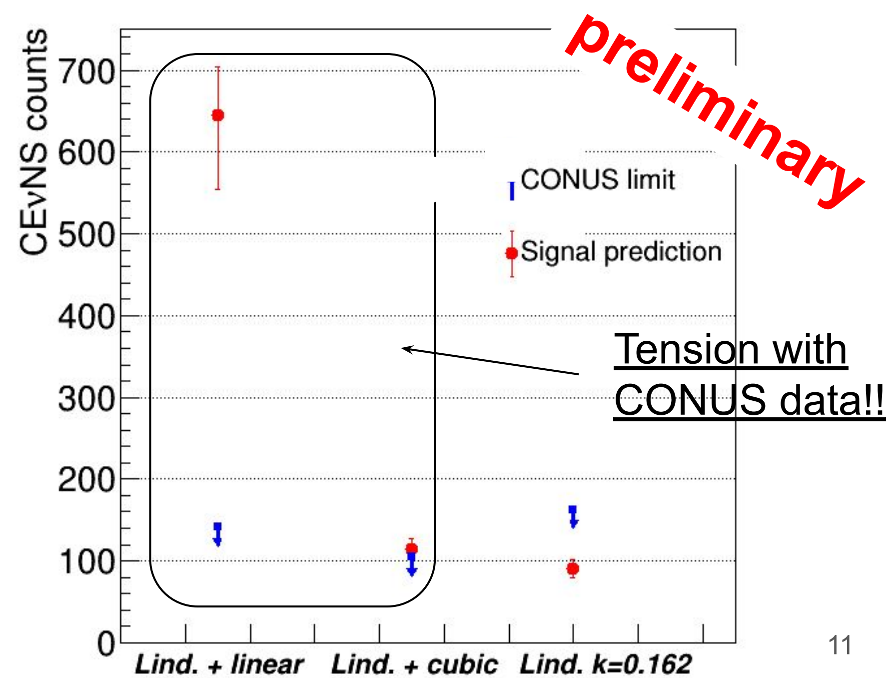
Abstract of Phys. Rev. Lett. 129, 211802 (2022)

The 96.4 day exposure of a 3 kg ultralow noise germanium detector to the high flux of antineutrinos from a power nuclear reactor is described. A very strong preference ($p < 1.2 \times 10^{-3}$) for the presence of a coherent elastic neutrino-nucleus scattering (CEνNS) component in the data is found, when compared to a background-only model. No such effect is visible in 25 days of operation during reactor outages. The best-fit CEνNS signal is in good agreement with expectations based on a recent characterization of germanium response to sub-keV nuclear recoils. Deviations of order 60% from the standard model CEνNS prediction can be excluded using present data. Standing uncertainties in models of germanium quenching factor, neutrino energy spectrum, and background are examined.

Lindhard model + linear/cubic parametrization at low energy.

Test NCC-1701 signal with CONUS data.



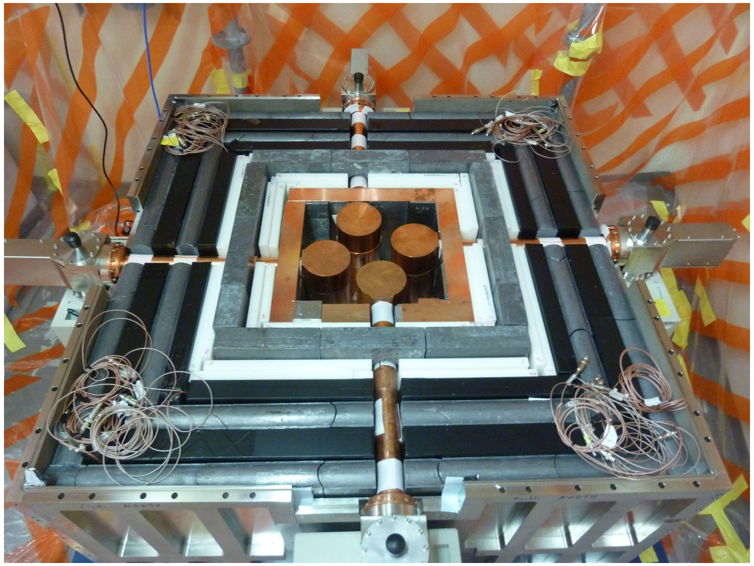


CONUS+

CONUS+ installation at the Leibstadt nuclear power plant (KKL) in Switzerland at 21 m from the reactor core during this summer .

The 4 Ge detectors of CONUS were upgraded, reducing the threshold below 200 eV.

Background characterization campaign completed. Shield adapted to the new background conditions.



Summary

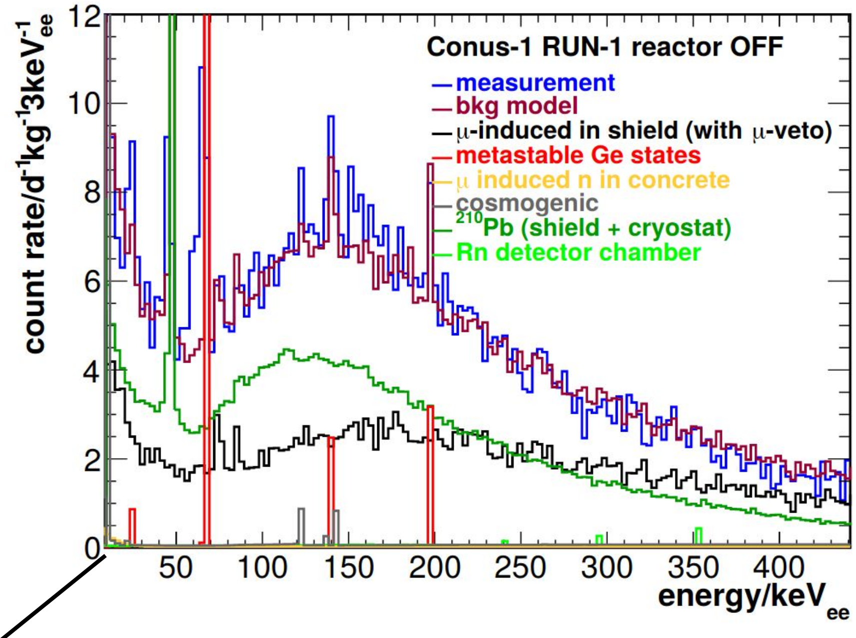
- Nuclear reactors: intense source of low energy (< 10 MeV) electron antineutrinos → CEνNS in fully coherent regime.
- CONUS experiment operated in Brokdorf nuclear power plant from April 2018 to December 2022.
- Upgrades during Run-5: improved environmental control and lower energy threshold due to new trigger algorithm.
- CONUS sets the best limit on CEvNS with reactor neutrinos: 90% C.L. limit is factor < 2 above Standard Model prediction.
- NCC-1701 signal in tension with CONUS data.
- Successor experiment CONUS+ in new location at NPP Leibstadt in installation. Site characterization and commissioning ongoing.

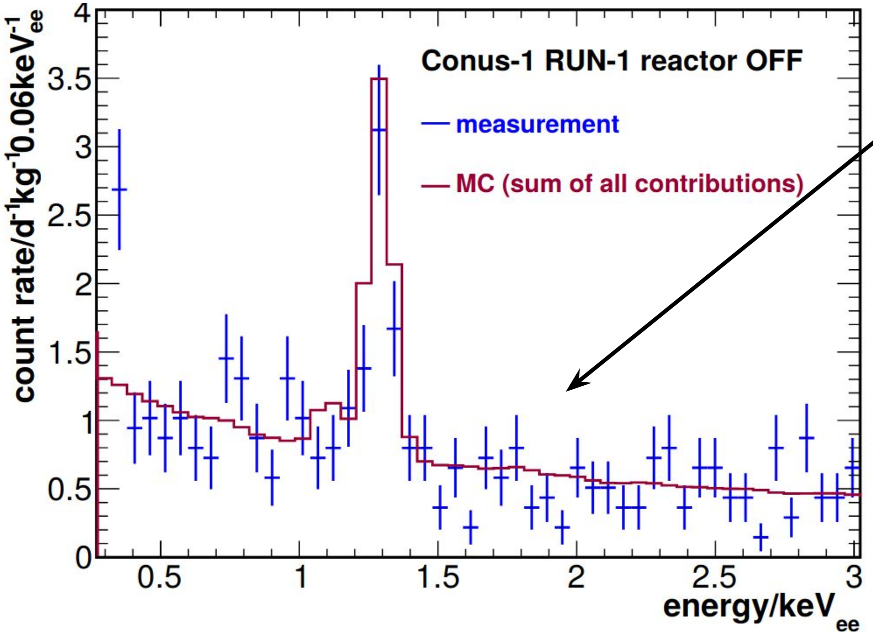
Thank you for your attention

Background in CONUS

Neutron spectrometry with NEMUS detectors with PTB and γ's measurements from non shielded HPGe detectors.

Reactor-correlated background inside shield negligible.





Background level in [0.5 − 1] keV_{ee} stable: ~10 counts/kg/d/keV_{ee} .

Residual background fully described by MC simulations.

J. Hakenmueller et al., Eur. Phys. J. C (2019) 79, 699
CONUS Collaboration, arXiv:2112.09585

Reactor-correlated background

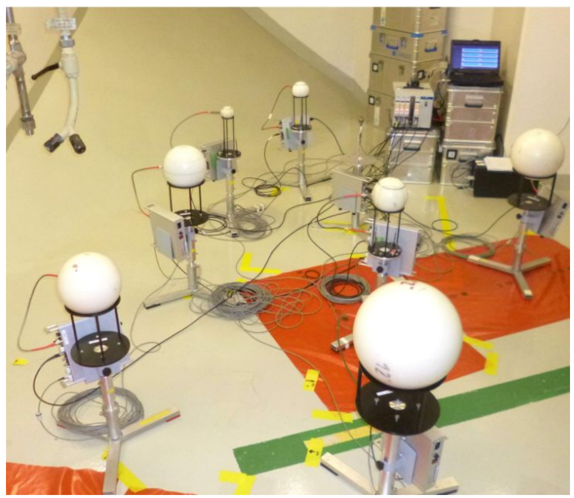
Reactor-correlated backgrounds are critical for CONUS since they can mimic a CEvNS signal.

Neutron spectrometry with NEMUS detectors by PTB and γ's measurements from non shielded HPGe.

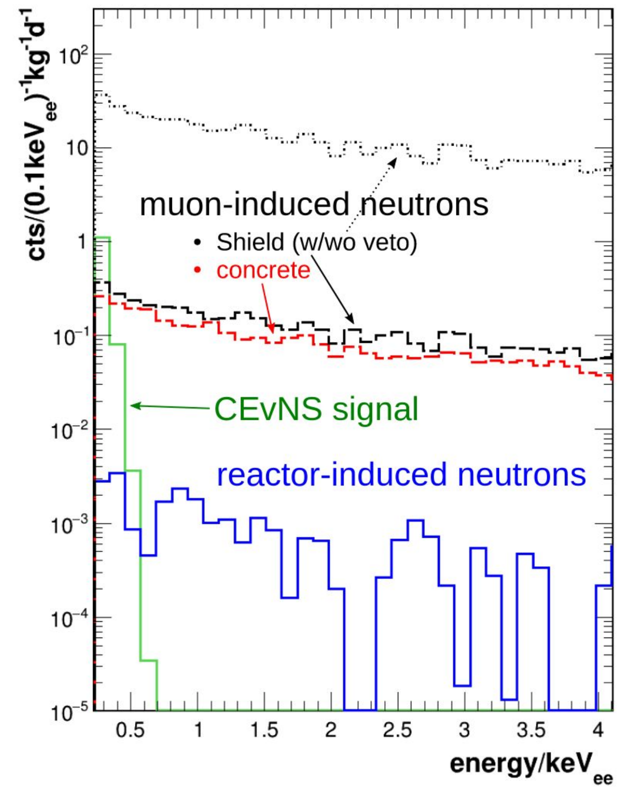
Neutron flux in CONUS room suppressed by factor >10^{20}.

Neutron field highly thermalized (>80%).

Correlated with thermal power.



MC propagation of residual fluence inside shield



PTB

<u>Negligible reactor-correlated contributions inside CONUS shield!</u>

Quenching measurement

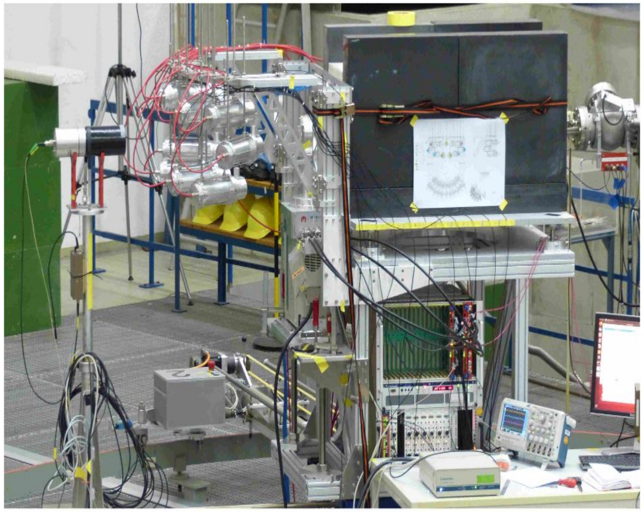
CONUS and PTB collaboration for a direct, model-independent (purely kinematics) measurement using neutrons (nuclear recoils).

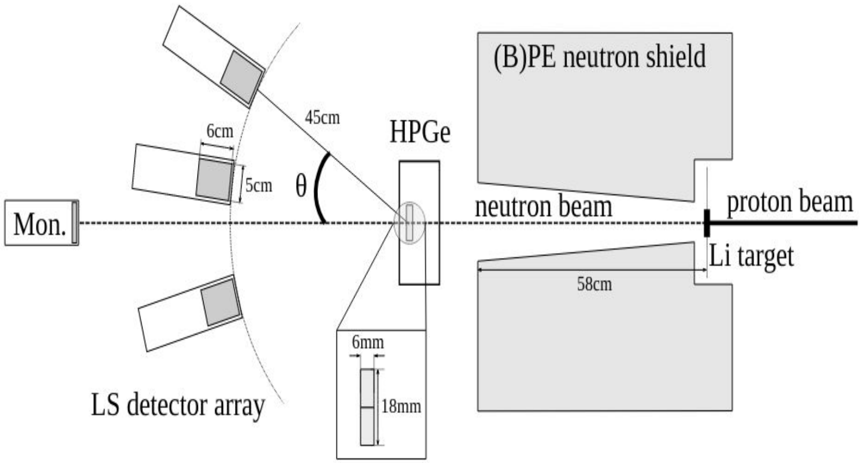
Scientific cooperation with PTB. PIAF pulsed proton beam to generate mono-energetic neutron beams via Li(p,n) reaction.

Dedicated thin HPGe as target (6 mm thick).

Triple time coincidence: beam stop – target HPGe – liquid scintillator detectors.

Angles varied between 18-45° (1° precision) and neutron beam from 250 to 800 keV
→ <u>nuclear recoils: 0.4 - 6 keV</u>





Non-standard interactions

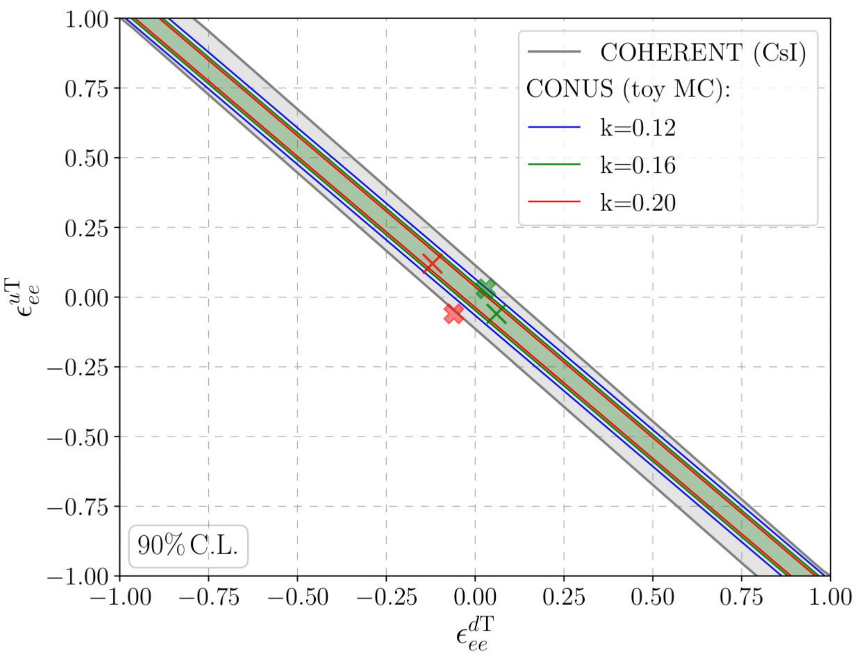
CONUS Collaboration,
J. High Energ. Phys. 2022, 85 (2022)

CONUS is sensitive to physics beyond the standard model, as non-standard neutrino-quark interactions. New coupling with nuclear charge term adding to CEvNS cross-section:

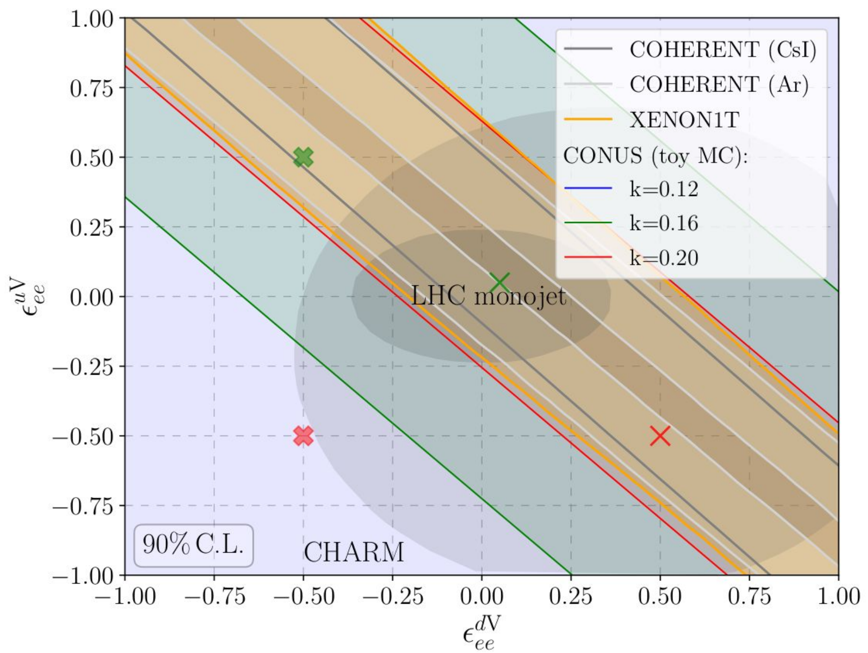
$$\left(\frac{d\sigma}{dT_N}\right) = \left(\frac{d\sigma}{dT_N}\right)_{CE\nu NS} + \frac{4G_F^2 M}{\pi} Q_{NSI}{}^2 \left(1 - \frac{MT_N}{4E_\nu^2}\right).$$

ROI: 0.3-1 keV
Exposure: 208 kg*d ON 38 kg*d OFF

Tensor-type interaction



Vector-type interaction



Simplified models: Light mediators

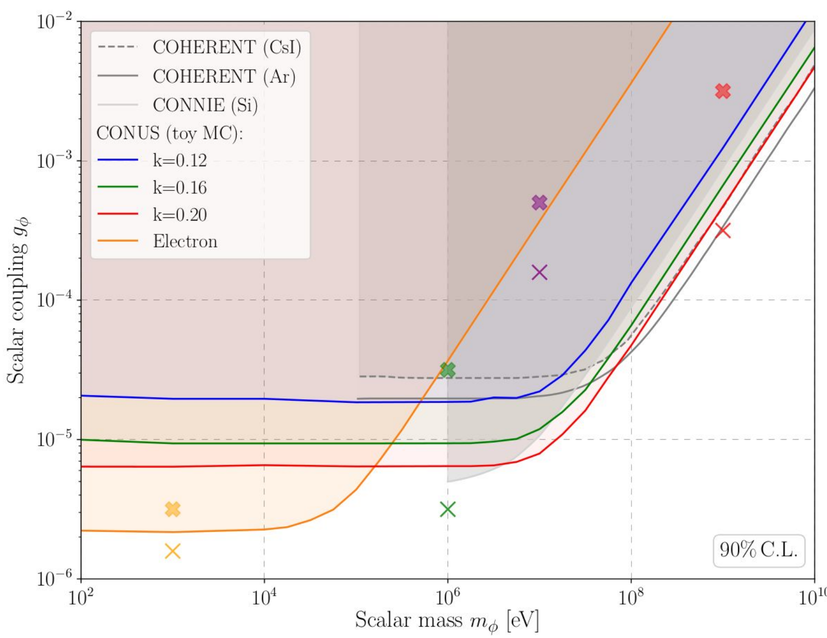
Test simplified mediator models that contribute to **CEvNS** / **EvES** assuming universal couplings to quarks / neutrinos.

Reactor neutrinos for low masses and π-DAR neutrinos for higher masses.

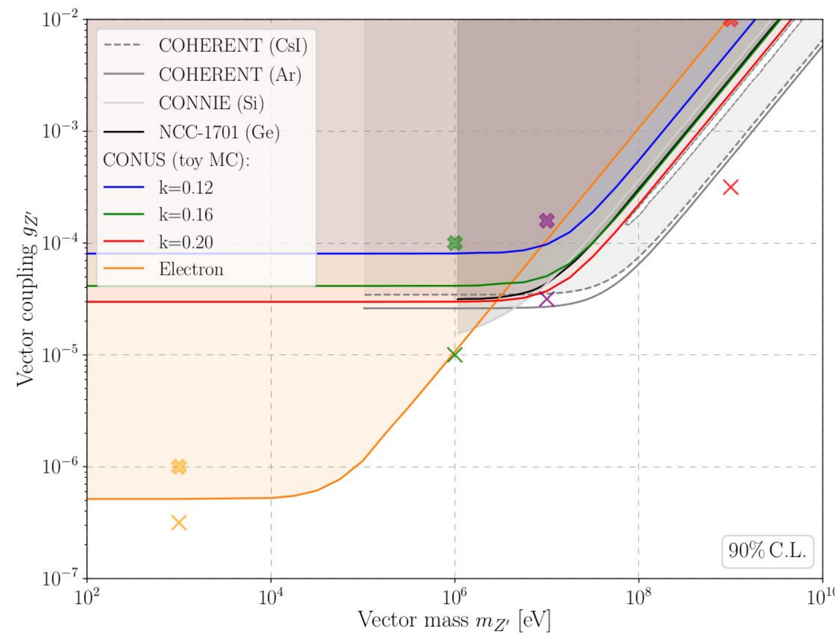
ROI: 0.3-1 keV
Exposure:
208 kg*d ON 38 kg*d OFF

ROI: 2-8 keV
Exposure:
649 kg*d ON 93 kg*d OFF

Scalar mediator



Vector mediator



CONUS Collaboration, J. High Energ. Phys. 2022, 85 (2022)

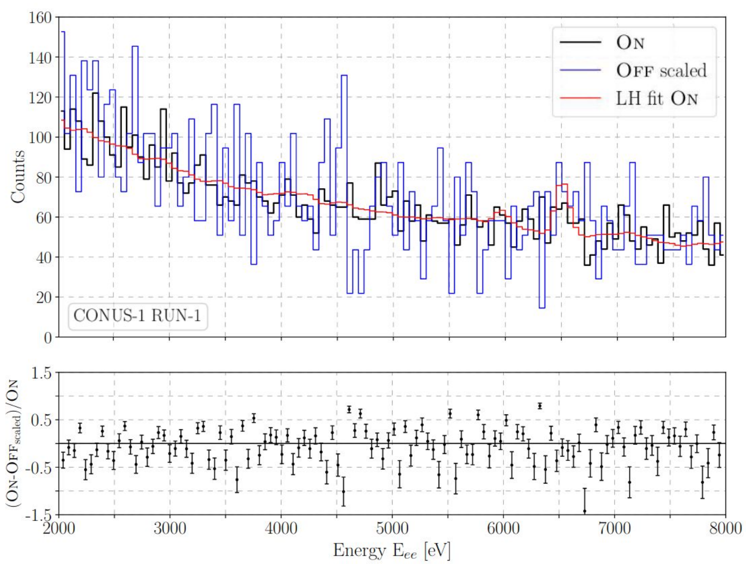
Neutrino electromagnetic properties

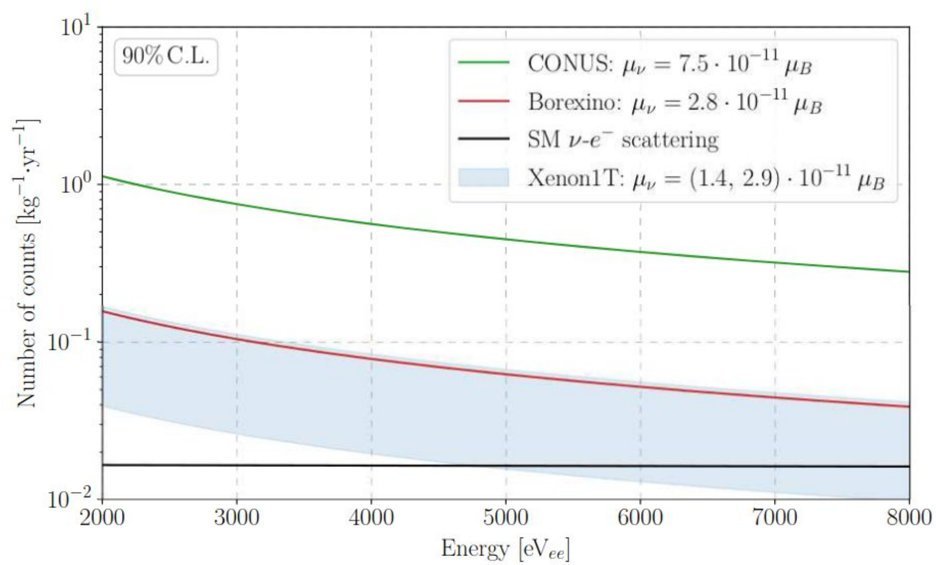
It is possible to study the neutrino magnetic moment from electron scattering at reactor site:

CONUS Collaboration,
arXiv:2201.12257

$$\left(\frac{d\sigma}{dT_e}\right)_{\nu MM} = \frac{\pi\alpha_{em}^2}{m_e^2}\left(\frac{1}{T_e}-\frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_e}}{\mu_B}\right)^2 \cdot$$

ROI: 2-8 keV
Exposure: 689 kg*d ON 131 kg*d OFF



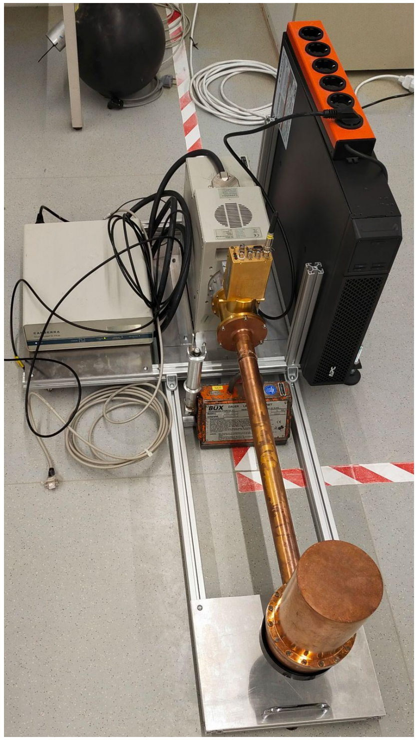


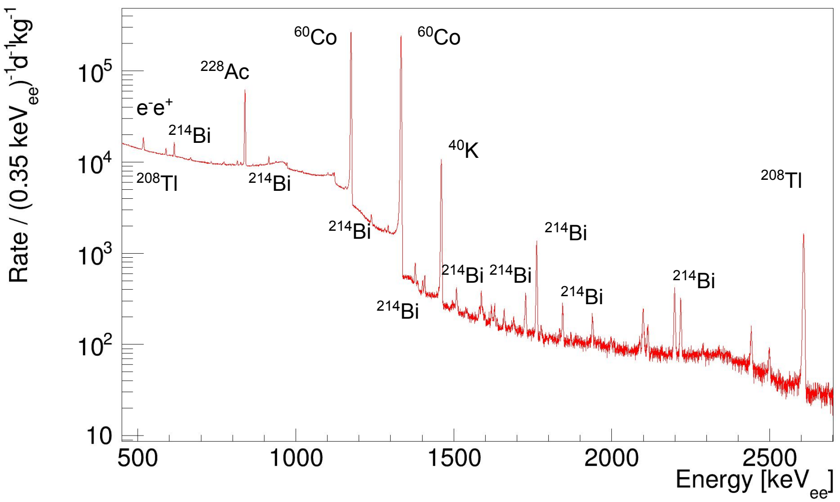
$\mu_\nu < 7.5\ 10^{-11}\ \mu_B$ (90% C.L.)

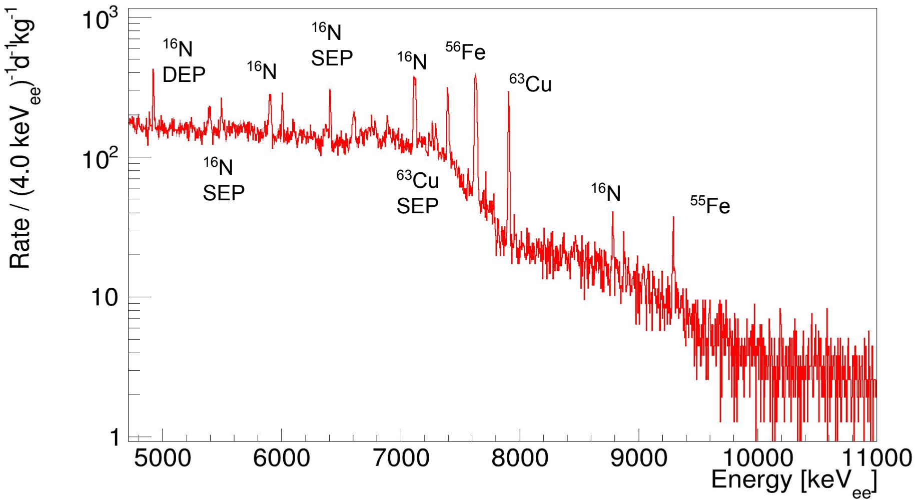
$q_\nu < 3.3\ 10^{-12}\ e_0$ (90% C.L.)

CONUS+ background: γ's

- Ultra-low background p-type coaxial HPGe detector CONRAD (m =2.2 kg). Electrical cryocooling system.
- Scan over different positions with measurement from few hours to one day.
- High energy gamma contribution (>2.7 MeV) factor 25 smaller than at Brokdorf power plant. Stronger contribution of ^{60}Co lines.

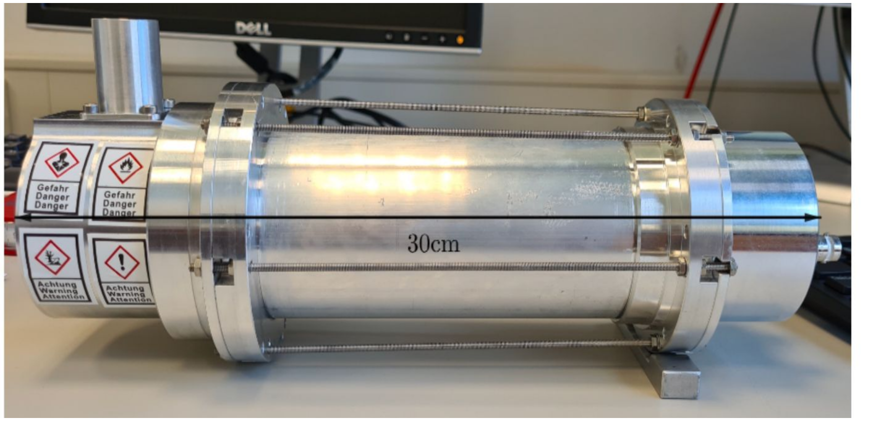


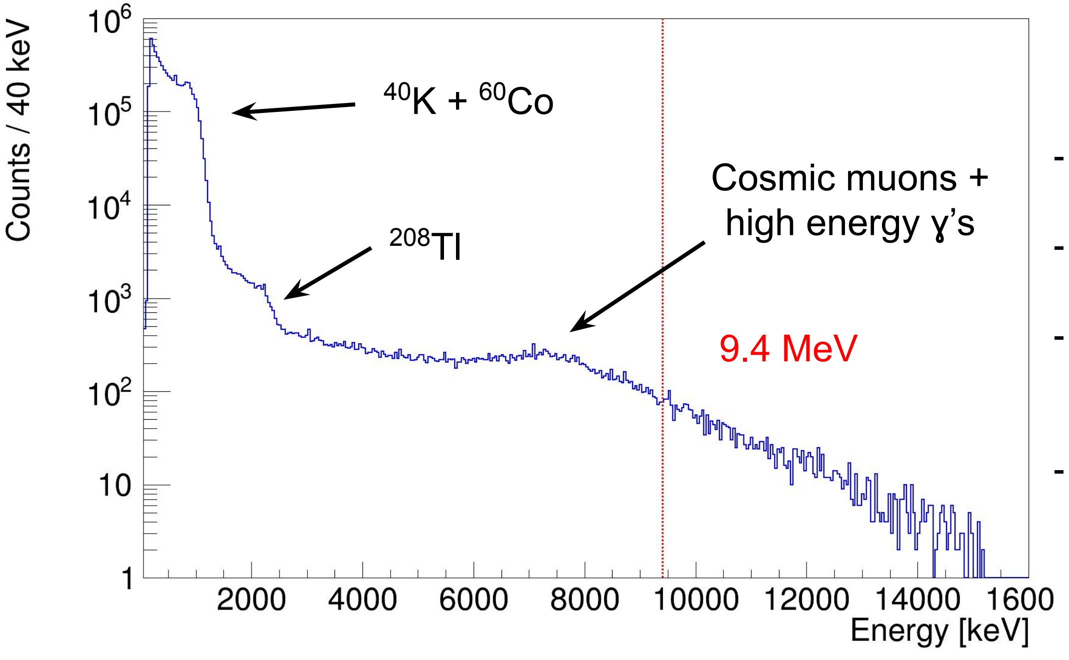




CONUS+ background: Cosmic muons

- Liquid scintillator cell filled with 120 ml of "Ultima Gold". PMT for light detection.
- Measurements at MPIK and KKL for comparison.
- Quality cuts applied: saturation, pile-up.
- Pulse shape discrimination cut to remove neutrons.

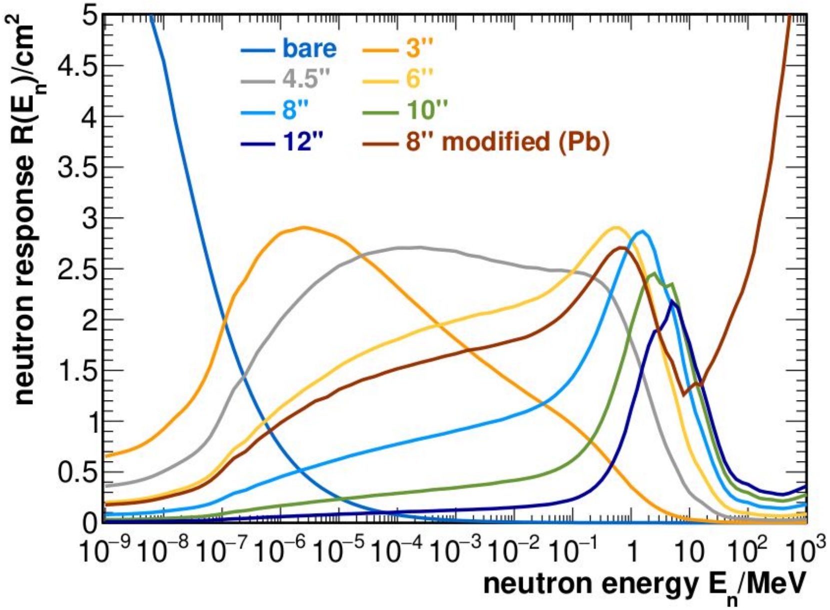


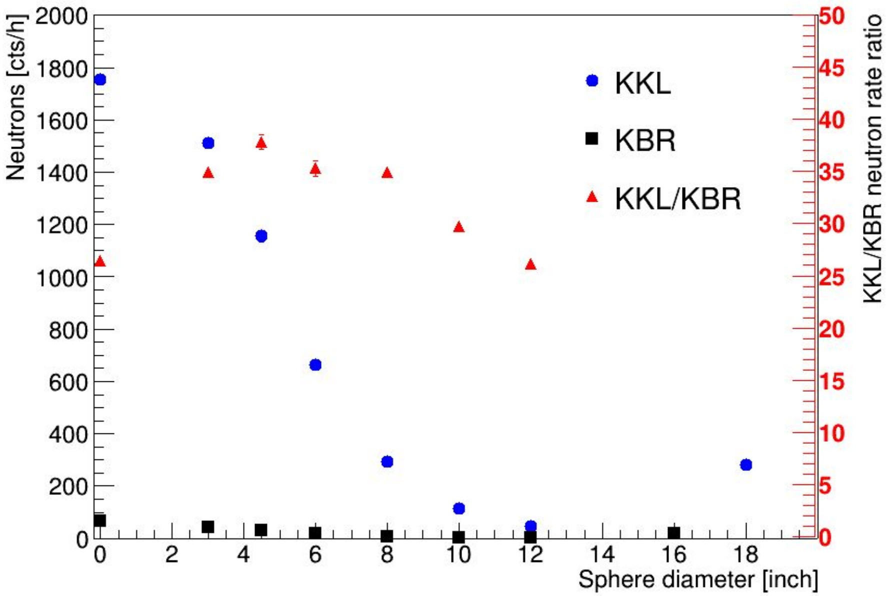


- Energy cut at 10 MeV to avoid environmental radioactivity and high energy gamma contribution.
- <u>Muon rate outside: 0.121 Hz.</u>
- <u>Muon rate in KKL: 0.058 Hz.</u>
- Reduction factor of 2.1 in KKL compare to surface → overburden ~7-8 m.w.e.
- Muon rate factor 2.2 larger than at KBR.

CONUS+ background: Neutrons

- Neutron spectrometry with Bonner Sphere detectors in scientific cooperation with PSI.
- Monitoring of thermal and fast neutrons during whole measurement campaign. Neutron flux stable within 3%.
- Same configuration of spheres as in KBR for direct comparison giving a sensitivity from 10^{-9} to 10^{3} MeV
- Neutron flux ~30 times larger than in KBR. However, it is still a subdominant contribution of the background in the region of interest.





J. Hakenmueller et al., Eur. Phys. J. C (2019) 79, 699

Physics potential